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CERN, Geneva, Switzerland

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INTRODUCTION

In order to monitor particle losses in the LHC and dump the beam if the losses risk to quench the superconducting magnets, a beam loss monitor (BLM) system will be installed around the ring [1]. This system consists of ionization chambers that will detect secondary shower particles outside the magnet cryostat. The BLMs are primarily designed for protons but will also be used during heavy-ion runs, starting with $^{208}\text{Pb}^{82+}$ beams. Changes need to be made to the present design in order to also monitor the Pb^{82+} losses. Simulations of the ratio between heat deposition in the superconducting coils of a magnet and the signal in the BLM system for both heavy ions and protons allow us to evaluate the species dependence of the thresholds for dumping the beam. Furthermore some extra BLMs need to be added to monitor loss locations that are specific to ion operation. These losses are caused by the inefficiency of the collimation system and by nuclear electromagnetic interactions at the interaction points (IPs).

BEAM DUMP THRESHOLDS

Simulation Setup

In order to evaluate whether the thresholds for beam dumping need to be adjusted between the Pb^{82+} and proton runs, the Monte Carlo code FLUKA [2,3] was used to simulate the shower development in a magnet. The detailed geometry of a main dipole magnet (MB) was implemented in FLUKA and the BLMs were schematically modelled as thin rectangular iron boxes filled with nitrogen, placed outside the MB cryostat. A detailed description of the geometry can be found in [4].

A generic beam loss was represented by a pencil beam at nominal LHC energy impinging on the inside of the vacuum chamber with an incident angle of 0.25 mrad and the shower was simulated in FLUKA. During the simulation, the energy deposition in the beam screen, the superconducting coils and in the BLMs was scored.

Simulations were done with both 7 TeV protons and 2.76 A TeV Pb^{82+} ions.

Results

The resulting energy deposition profiles in the hottest superconducting wire in the MB coil and in the BLMs are shown in Figure 1. In order to facilitate the comparison, the curves for the Pb^{82+} ions have been scaled with energy per nucleon and number of nucleons, which is the same as scaling with charge, since the magnetic rigidity has to be constant. As can be seen in the figure, the two particle types have almost identical profiles. This means that the ratio between the heat deposited in the coils and the energy deposition in the BLMs is about the same for ions and protons and thus that the same thresholds for the beam dump can be used.

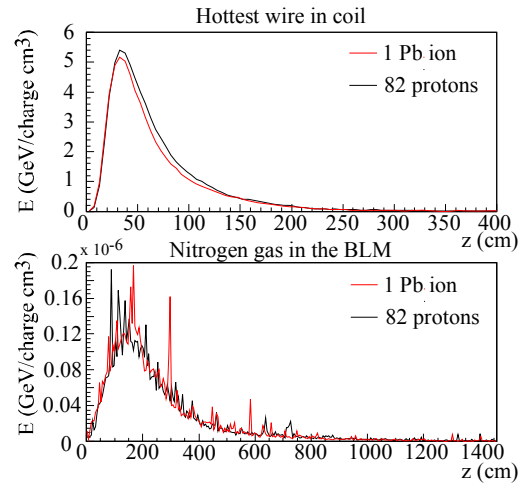


Figure 1: The energy deposition in the hottest wire in the coil and in the N_2 gas inside the BLM for Pb ions and 82 protons.

Physics Discussion

The fact that the thresholds are the same for both species might seem counter-intuitive at first. Therefore we shall give a short account of the important physical processes to explain why this is the case.

The most important process where the energy loss in a material differs between heavy ions and protons is the ionization, which is well described by the familiar Bethe-Bloch formula. From this formula it is clear that the stopping power depends on the square of the charge of the impinging particle, which would imply that the Pb^{82+} ions should lose a factor 82^2 more energy per unit path length than protons after the entry into the material. This different stopping power might be a reason to expect that the heating of the coils should be much higher from Pb^{82+} ions.

However, the heavy ions lose only a small part of their energy through ionization. When ions penetrate into a

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material, they start to break up into fragments through nuclear interactions and electromagnetic dissociation and the stopping power from ionization decreases until the nucleus is either totally fragmented into independent nucleons or the remaining fragments are so slow that they stop. Further FLUKA simulations show that, after 10 cm on average, the heaviest fragment of a 2.76 A TeV Pb^{82+} ion hitting a copper block has around 15% of the initial mass and after 27 cm it is totally decomposed into individual nucleons. Over this distance, the initial Pb^{82+} ion loses much less than 1% of its energy through ionization according to the Bethe-Bloch formula. The main part of the energy is instead deposited through the hadronic shower, which behaves similarly for ions and protons. This means that the macroscopic energy deposition should be roughly the same for the two particle types and that is what is important to consider, since the heat deposition on a 1 cm scale (on the order of the minimum propagating zone of the superconducting cables [4]) is what determines if the magnet quenches.

One must bear in mind that the lost particles in the LHC first hit the beam screen at a small angle before the shower spreads to the coils. This means that the primary lost particle will actually traverse a large distance inside the beam screen. The ionization energy loss is a very local process, since low energy electrons are created that do not travel far before they stop. Therefore it is reasonable to expect that the energy deposition from ions and protons should differ on a small scale in the beam screen but not in the coil, which is only reached by the hadronic shower.

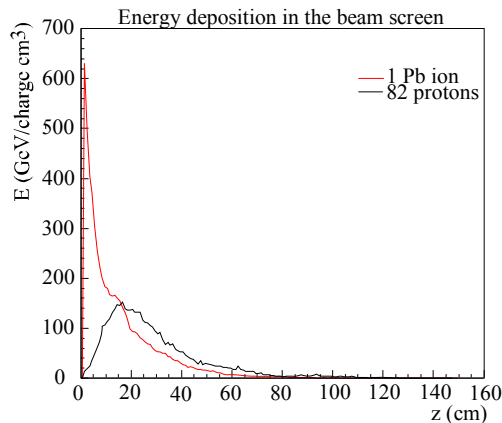


Figure 2: The energy deposition for Pb ions and protons at LHC energy in the innermost 0.1 mm of the beam screen.

A FLUKA simulation shown in Figure 2, where the energy deposition in the beam screen was scored in a mesh of $0.1 \times 0.1 \text{ mm}^2$ transversely, shows that this is the case. If instead the energy deposition is averaged over 1 cm^3 , the difference between ions and protons is very small, meaning that the same thresholds can be used.

Only a main dipole magnet was simulated, but the above result is valid also for other magnet types where the design of the beam screen is similar.

EXTRA BLMS FOR COLLIMATION

The LHC collimation system has been designed for proton beams of high intensity and is based on a two-stage collimation concept, with short primary collimators intercepting particles, and long secondary collimators downstream where the halo particles, scattered off the primaries, deposit their energy in hadronic showers. In spite of having 100 times less beam power, problems arise for ion collimation owing to different mechanisms of particle-collimator interaction: hadronic fragmentation and electromagnetic dissociation upon impact on primary collimators result in the production of particles with small angular divergence and different Z/A ratio. These can fail to be intercepted by secondary collimators and produce significant heat load in the superconducting magnets with risk of quenches. At present the cleaning efficiency falls short by about a factor of 2 for the nominal $^{208}\text{Pb}^{82+}$ ion beam at collision energy and therefore a suitable system of monitoring loss spots has to be put in place. Simulation studies for ion collimation have been carried out using the ICOSIM program, which combines particle tracking capabilities with treatment of heavy ion specific interactions. A detailed description of the program can be found elsewhere [7].

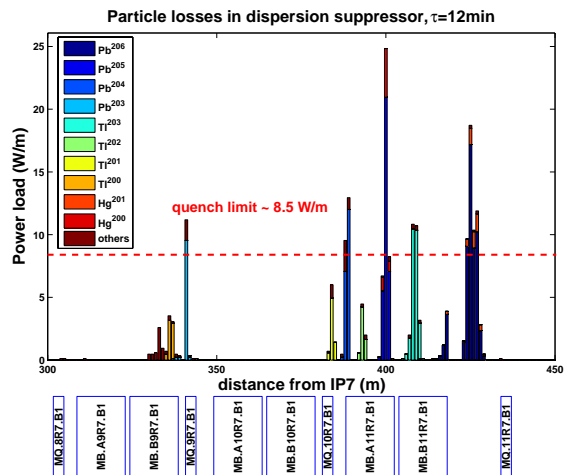


Figure 3: Heat deposition in the dispersion suppressor at collision energy.

Figure 3 shows a loss map produced by ICOSIM for a nominal LHC heavy ion beam at collision energy: losses are limited to the dispersion suppressor region downstream of the betatron collimation section and the heat load exceeds the conventional quench limit of the SC magnets [5] by more than a factor of 2 (but note that [4] makes a case for a higher limit).

A similar pattern of losses has been observed at collision energy in simulations for the second beam, circulating counter-clockwise. At injection energy, on the other hand, losses tend to be more spread out longitudinally, while keeping well below the expected quench limit (generally less than 1 W/m). The loss pattern's dependence on orbit movements has been estimated for the time being with a study of the effect of

changes in the aperture on the peaks positioning and heat load distribution. An increase (decrease) of the aperture by a few mm tends to produce a shift downstream (upstream) of the loss peaks of up to 10 m, but still keeping within the limits of the dispersion suppressor region. Given this uncertainty and the fact that the loss peaks at collision energy tend to be very sharp and localised, a very tight coverage of the dispersion suppressor area with BLMs is proposed: a 2.5 m spacing in between chambers, corresponding to the FWHM of the energy deposition signal in gas (as shown in Figure 1), has been assumed in this scheme for both circulating beams to ensure full detection of losses in the region.

BLMS FOR MONITORING COLLISIONAL PROCESSES

When the Pb^{82+} ion beams collide at an IP, a number of nuclear electromagnetic processes peculiar to ion operation take place [5,6]. Some of these cause the ions to change their charge to mass ratio, meaning that the affected ions will create secondary beams that will leave the design trajectory and be lost somewhere in the machine. These secondary beams can cause a high localized energy deposition that may quench a magnet and it is thus important to monitor the spots where these ions are lost.

The most dangerous process is Bound Free Pair Production (BFPP), where one of the colliding ions captures an extra electron resulting in a secondary beam emerging from the IP. The danger of a quench due to the BFPP beam has already been investigated [4] and it was concluded that the BFPP beam is not likely to quench a main LHC dipole if it hits in the middle of the magnet. However, if the beam instead hits near the end it could be more dangerous. Experiments at RHIC have shown that orbit errors can easily move the BFPP spot by several metres [8]. Therefore it is of highest importance to monitor this loss and add extra BLMs if the expected impact locations are not already covered by those foreseen for protons. The latter are mounted on all quadrupoles in the arcs and dispersion suppressors.

To determine the impact locations of the BFPP beam on both sides of every IP where ions may collide (IP1, IP2, IP5), ions with the appropriate change of magnetic rigidity were tracked in the LHC lattice in the Madtomma environment, as in [6]. An example of the tracking is shown in Figure 4.

From the tracking, locations of BLMs that needed to be added were determined. The losses follow the dispersion function along s , and in all cases a part of the beam envelope at one σ escapes the first impact location and is instead lost further downstream. Both these loss locations have to be covered by extra BLMs.

Another process that takes place at the IP is electromagnetic dissociation (EMD). Here an ion loses one or two neutrons. In the first case, the change in magnetic rigidity remains within the momentum

acceptance of the arcs so that these ions will be absorbed in the momentum-cleaning insertion with a rate determined by the contribution of this process to the luminosity lifetime, $1/(\text{a few hours})$ at most [5,6]. In the second case, loss spots are formed in the dispersion suppressors but the rate is too small to provoke quenches. Thus no extra BLMs need to be installed to monitor losses from EMD.

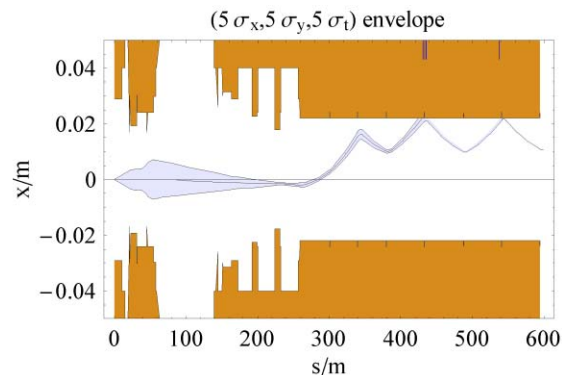


Figure 4: The 5σ envelope of the BFPP beam in the x - s plane coming out of IP 1 and hitting the beam screen 430 m downstream. Proposed extra BLMs for the nominal scheme are shown as blue lines at the top of the picture. A small fraction of the beam continues further downstream.

CONCLUSIONS

The energy loss of $^{208}\text{Pb}^{82+}$ ions and protons inside a material is different because of the high ionization cross section of the ions. However, when lost particles hit the inside of an LHC magnet, the difference is only visible in the beam screen. This implies that the ratio between heat deposition in the coils and BLM signal is approximately the same for Pb^{82+} ions and protons and that the same thresholds for dumping the beam can be used.

Extra BLMs are needed for the ion operation to monitor losses from collimation and from BFPP. The expected loss locations have been determined by appropriate tracking methods in each case and an installation of BLMs has been specified. EMD does not pose a threat to the machine and no extra BLMs are needed for this process.

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